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Capturing Natural Resource Dynamics in Top-Down Energy-Economic Equilibrium Models

Da Zhang[*†§], Valerie Karplus[‡], and Sebastian Rausch[⋆]

Abstract

Top-down energy-economic modeling approaches often use deliberately simple techniques to represent heterogeneous resource inputs to production. We show that for some policies, such as feed-in tariffs (FIT) for renewable electricity, detailed representation of renewable resource grades is required to describe the technology more precisely and identify cost-effective policy designs. We extend a hybrid approach for modeling heterogeneity in the quality of natural resource inputs required for renewable energy production in a stylized computable general equilibrium (CGE) framework. Importantly, this approach resolves near-flat or near-vertical sections of the resource supply curve that translate into key features of the marginal cost of wind resource supply, allowing for more realistic policy simulation. In a second step, we represent the shape of a resource supply curve based on more detailed data. We show that for the case of onshore wind development in China, a differentiated FIT design that can only be modeled with the hybrid approach requires less than half of the subsidy budget needed for a uniform FIT design and proves to be more cost-effective.

Contents

1. INTRODUCTION

Top-down modeling approaches specify technology in a deliberately simple manner, even as they offer important insights because they account for endogenous adjustment of prices and quantities in response to policy. While this approach is often justifiable when the question under investigation does not depend on a precise representation of technology, for some applications additional technological detail can be critical to the design and evaluation of alternative policy

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proposals. Because of the discrete nature of engineering design or resource quality, the cost curves associated with the application of many technologies are known to be kinked. For example, a modeler may wish to capture the cost of reducing emissions as a function of the costs of competing alternatives—for instance, efficiency improvement, end-of-pipe emissions removal, and a displacement with a non-emitting renewable resource. Within each of these alternatives, the number of distinct technological options and their properties can matter significantly to the optimal choice of a solution. Oversimplifying can introduce substantial errors when estimating abatement costs of policy.

In this paper, we extend an integrated (bottom-up in top-down) hybrid approach that is more flexible and precise than traditional approaches used in CGE models, taking as our starting point the procedure developed in Kiuila and Rutherford (2013). This innovation is especially useful if the shape of cost curve is not regular, for instance, it has large steps or is not simply convex or concave. This procedure is generalizable to any many-step aggregated abatement cost curve representing different abatement technologies or a technology that requires heterogeneous resources as an input.

We detail the application of this hybrid approach by showing its ability to accurately capture the dynamics of technology for electricity generation from wind. The hybrid approach has a distinct advantage in is its capability to replicate a "wind rush" phenomenon, in which large quantities of wind capacity are cyclically deployed upon reaching a threshold electricity price (as a function of an implicit or explicit subsidy). However, this effect cannot be captured by the traditional approach, which relies on smooth curve fits for resource representation. As we will show, the hybrid approach also allows for the simulation of policies targeted at different grades of resource, e.g. a differentiated FIT policy. By explicitly representing each grade of resource, threshold levels for policy incentives can be assigned, and impacts assessed, more precisely. Resource-differentiated policies have been widely applied and drawn more attention as they require a smaller subsidy budget.

The rest of the paper is structured as follows. In Section 2, we briefly summerize the previous work on representing technology in top-down models. Section 3 constructs a simple, stylized top-down economic model and applies it to demonstrate the application of this hybrid approach, illustrate the "wind rush" phenomenon and its advantages compared to traditional approaches. Section 4 provides a real-world example of how the same method can be extended using data for China's economy and onshore wind resources. The final section discusses the results and policy implications.

2. PREVIOUS WORK

Previous efforts have focused on adding technological detail to top-down models. Here we consider a specific class of top-down models, energy-economic computable general equilibrium (CGE) models. Efforts to introduce additional technology detail include models applied in the Energy Modeling Forum 29's Border Carbon Adjustment study (Böhringer *et al.*, 2012), the PET model (O'Neill *et al.*, 2010), the PACE model (Hermeling *et al.*, 2013), and the MIT EPPA model (Chen *et al.*, 2015). All of these examples involve introducing energy-related technologies using the existing constant elasticity of substitution formulation, which requires smooth curve fits for estimation of key response parameters, including resource requirements.

The block decomposition algorithm suggested by Böhringer and Rutherford (2009) can be used to couple top-down and bottom-up sub-models using an iterative procedure to solve for a consistent general equilibrium response in both models. Rausch and Mowers (2014) applied this technique to integrate two large-scale simulation models, the MIT USREP model (Rausch *et al.*, 2010) and NREL's ReEDS model (Short *et al.*, 2011) to study distributional and efficiency impacts of clean and renewable energy standards for electricity in the United States. Though this method provides a comprehensive and consistent modeling framework, it requires both top-down and bottom-up sub-models that have been well established and calibrated to a consistent benchmark point, which is highly demanding for most modeling cases.

Another approach involves direct representation of bottom-up technological information within a general equilibrium framework described by Böhringer and Rutherford (2008). As proposed by Kiuila and Rutherford (2013), either a smooth curve (traditional approach, applied by Jorgenson *et al.* (2008), Morris *et al.* (2010), Boeters and Bollen (2012), Springmann (2014)) or a Leontief technology (hybrid approach, applied by Koopmans and Velde (2001), Frei *et al.* (2003), Jacoby *et al.* (2006), Laitner and Hanson (2006), Sue Wing (2008)) can be applied to integrate of bottom-up abatement costs with top-down models[1]. By implementing both approaches to represent a bottom-up cost curve developed in the McKinsey report (McKinsey report, 2009) within a top-down static model (Imhof and Rutherford, 2010) to study the climate policy in Switzerland, Kiuila and Rutherford (2013) compare the results of these two approaches for the first time[2]. They found both approaches provide virtually the same results when the calibration process is precisely executed.

In this paper, we first show that the hybrid approach can more flexibly handle the near-flat or near-vertical sections of the resource supply curve that translate into key features of the marginal cost of resource supply. By demonstrating a many-step supply curve for China's onshore wind based on detailed wind resource data (Zhang *et al.*, 2014a) that can be integrated into a recursive dynamic top-down model, this paper then shows how a complex cost curve for abatement or resource-dependent production can be embedded directly or approximately using a step fitting method within a CGE model. It further demonstrates the importance of this technique for analysis of technology-specific policy that depends on detailed representation of the underlying technology.

[1] The traditional approach is more commonly used because constant-return-to-scale (CRTS) functions, e.g. constant-elasticity-of-substitution (CES) functions, are widely employed functional forms in top-down energy-economic models for environmental and climate policy assessment.

[2] The McKinsey curve used by Kiuila and Rutherford (2013) only has 8 steps. Moreover, the traditional approach in their paper will not be realistic when the policy is very stringent, because all the abatement technology options should be exhausted and a very high abatement cost should be given when the hybrid approach is applied, but the traditional approach in their case will give stable abatement cost even under very high abatement requirement due to its concave shape as calibrated.

3. A STYLIZED GENERAL EQUILIBRIUM MODEL

3.1 Hybrid Approach

We start our analysis by representing a heterogeneous resource using the hybrid approach in a stylized two-sector (resource-dependent good Y, for example, electricity, and other goods and services V), single-region general equilibrium model[3]. A backstop electricity technology BY, in this case wind, is distinguished from other fossil-based electricity generation in the benchmark. The stylized representation of the closed economy is displayed in **Table 1.**

Table 1. Illustrative benchmark social accounting matrix (SAM) for a closed economy.

	Y		V	W	CONS
	Fossil (FY)	**Wind (BY)**			
P_Y	950	50		-1000	
P_V			10000	-10000	
P_W				11000	-11000
P_L	-375	-10	-5000		5385
P_K	-375	-30	-5000		5405
P_F	-100				100
P_E	-100				100
P_{S_0}		-10			10

Note: P_Y – electricity sector; P_V – other goods and services; P_W – composite consumption good; P_L – labor; P_K – capital; P_F – fossil fuel; P_E – emissions allowance; P_{S_0} – wind resource that enters the generation mix in the benchmark.

We design a supply curve for wind electricity generation using a simple three-step curve with a large step for this stylized model. This design illustrates the potential loss of fidelity that can result from the representation in such a simple curve form. The static curve (assuming all the prices of variable inputs remain unchanged) is shown as below (see **Figure 1**). We assume wind electricity is a perfect substitute for fossil-based electricity, and the price of wind electricity therefore is equal to the electricity price.

The height and width of each step in the piecewise curve reflect the grade and potential, respectively, of different wind resources. For example, point (2, 1.04) and (5, 1.04) in **Figure 1** mean that the static supply of wind is five times the benchmark wind electricity production when the electricity price is 1.04 times of the benchmark electricity price holding all the input prices unchanged, and the potential of this grade of wind resource is three times the benchmark wind electricity production.

The basic model structure is similar to the static model discussed in Böhringer and Rutherford (2008), but here we assume the electricity producer using fossil fuel bears a significant share of cost for emissions allowances. This parameter setting can lead to a larger increase in the electricity price when the emissions cap constraint becomes more stringent in our policy

[3] The source code of this stylized model can be downloaded from http://www.energyda.com/cge.html.

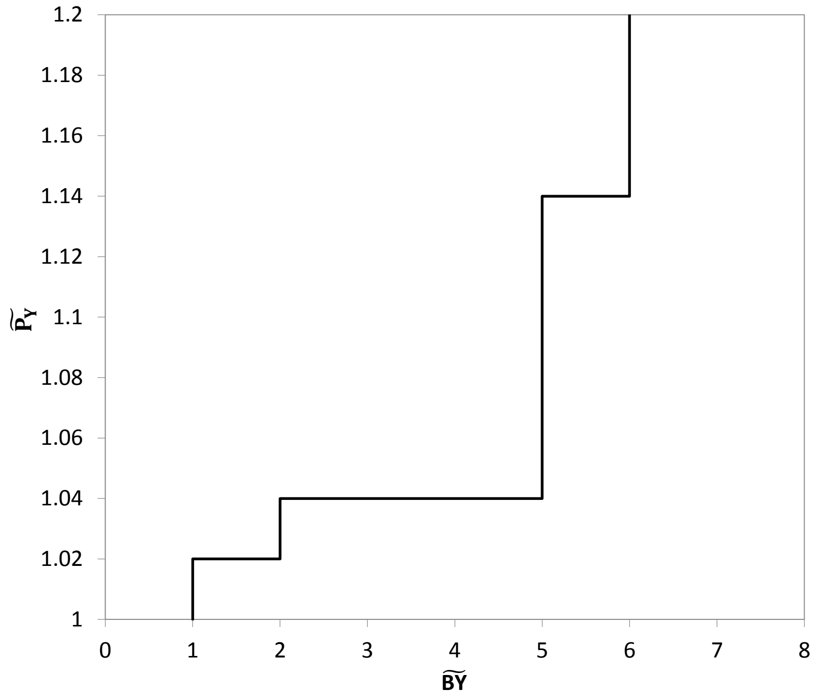

Figure 1. Supply curve of wind electricity generation assuming all the prices of variable inputs unchanged (BY – supply of wind electricity generation relative to the benchmark; P_Y – electricity price relative to the benchmark).

simulations, which will allow more backstop wind production to enter the generation mix. The model is structured in a MCP format, and decision variables are denoted as follows.

- Activity levels:

Y	is the production of electricity,
FY	is the production of electricity based on fossil fuel,
BY	is the production of electricity based on backstop technology (wind),
V	is the production of other goods and services, and
W	is the composite consumption (utility).

- Market prices[4]:

P_Y	is the price of electricity,
P_V	is the price of other goods and services,
P_W	is the price of composite consumption (utility),
P_L	is the price of labor,
P_K	is the price of capital,
P_F	is the price of fossil fuel,
P_E	is the price of emissions allowance
PS_0	is the price of the resource factor used in the benchmark wind production, and
PS_1, PS_2, and PS_3	are prices of the other three resource factors represented by the three steps.

[4] All the prices are calibrated to 1 or 0 in the benchmark.

• Income levels:

M is the income of the representative household.

The unit-profit function of V is[5]:

$$\Pi^V = P_V - \tilde{P}_L^{\theta_L^V} \tilde{P}_K^{1-\theta_L^V} \tag{1}$$

where

θ_L^V is the cost share of labor in production of V.

The unit-profit function of FY is:

$$\Pi^{FY} = P_Y - \left\{ \theta_{KL}^{FY} \left(\tilde{P}_L^{\theta_L^{FY}} \tilde{P}_K^{1-\theta_L^{FY}} \right)^{1-\sigma_F^{FY}} + \left(1 - \theta_{KL}^{FY}\right) \left(\theta_F^{FY} \tilde{P}_F + \theta_E^{FY} \tilde{P}_E \right)^{1-\sigma_F^{FY}} \right\}^{\frac{1}{1-\sigma_F^{FY}}} \tag{2}$$

where

θ_{KL}^{FY} is the cost share of the value-added composite in production of FY,
θ_L^{FY} is the cost share of labor within the value-added composite in production of FY,
θ_F^{FY} is the cost share of fossil fuel within the total cost of fossil fuel and emissions allowances in production of FY,
θ_E^{FY} is the cost share of emissions allowances within the total cost of fossil fuel and emissions allowances in production of FY,
σ_F^{FY} is the elasticity of substitution between the value-added composite and fossil fuel in production of FY.

The wind electricity generation is represented using the hybrid approach suggested by Kiuila and Rutherford (2013). Wind electricity generation technology using capital, labor and different grades of resources (i.e. different classes of wind) is able to produce a good that is identical to the output of fossil-based electricity technology. In our example, we distinguish four grades of wind resources by different fixed resource factors. The price of the resource factor used in the benchmark wind production is PS_0, and prices of the other three represented by the three steps are PS_1, PS_2, and PS_3 respectively. The unit-profit function of the benchmark wind production BY_0 and backstop productions BY_i ($i = 1, 2, 3$) are:

$$\Pi^{BY_0} = P_Y - \left\{ \theta_{KL}^{BY_0} \left(\tilde{P}_L^{\theta_L^{BY_0}} \tilde{P}_K^{1-\theta_L^{BY_0}} \right) + \left(1 - \theta_{KL}^{BY_0}\right) \tilde{PS}_0 \right\} \tag{3}$$

[5] The price with a tilde represents the relative price to the benchmark price.

$$\Pi^{BY_i} = P_Y - \left\{ \mu_{KL}^{BY_i} \left(\tilde{P}_L^{\theta_L^{BY_i}} \tilde{P}_K^{1-\theta_L^{BY_i}} \right) + \alpha^{BY_i} PS_i \right\} \tag{4}$$

respectively, where

$\theta_{KL}^{BY_0}$	is the cost share of the value-added composite in production of BY_0,
$\theta_L^{BY_0}$	is the cost share of labor within the value-added composite in production of BY_0,
$\theta_L^{BY_i}$	is the cost share of labor within the value-added composite in production of BY_i,
$\mu_{KL}^{BY_i}$	is the mark-up parameter for the cost of production of BY_i[6], and
α^{BY_i}	is the quantity of fixed resource factor used in one unit production of BY_i.

In this model, we apply the simplification that the utility good W is identical to the final consumption demand, which can be characterized by a composite good of V and Y. The unit-profit function of W is:

$$\Pi^W = P_W - \left\{ \theta_V^W \tilde{P}_V^{1-\sigma_V^W} + \left(1 - \theta_V^W\right) \tilde{P}_Y^{1-\sigma_V^W} \right\}^{\frac{1}{1-\sigma_V^W}} \tag{5}$$

where

θ_V^W	is the share of other goods and services V in the final demand, and
σ_V^W	is the compensated elasticity of substitution between other goods and services V and electricity Y in the final demand.

Zero-profit conditions that determine the activity levels of all the above production and consumption are as follows:

$$-\Pi^V \geq 0 \perp V \geq 0 \tag{6}$$

$$-\Pi^{FY} \geq 0 \perp FY \geq 0 \tag{7}$$

$$-\Pi^{BY} \geq 0 \perp BY \geq 0 \tag{8}$$

$$-\Pi^W \geq 0 \perp W \geq 0. \tag{9}$$

A representative household in our stylized model is endowed with labor, capital, fossil fuel, emissions allowances, and different grades of resources for wind electricity production. The total income of the representative household is given as follows:

$$M = P_L\overline{L} + P_K\overline{K} + P_F\overline{F} + P_E\overline{E} + P_{S_0}\overline{S_0} + \sum_i P_{S_i}\overline{S_i} \tag{10}$$

where

$\overline{L}$	is the aggregate labor endowment,
$\overline{K}$	is the aggregate capital endowment,
$\overline{F}$	is the aggregate fossil fuel endowment,
$\overline{E}$	is the total initial emissions allowances,
$\overline{S_0}$	is the endowment of wind resource used in the benchmark wind production BS_0, and
$\overline{S_i}$	is the endowment of wind resource used in the backstop wind production BS_i.

Market clearance conditions that determine all the prices are determined as follows:

$$\overline{L} \geq \frac{\partial V}{\partial P_L}V + \frac{\partial FY}{\partial P_L}FY + \frac{\partial BY_0}{\partial P_L}BY_0 + \sum_i \frac{\partial BY_i}{\partial P_L}BY_i \ \perp \ P_L \geq 0 \tag{11}$$

$$\overline{K} \geq \frac{\partial V}{\partial P_K}V + \frac{\partial FY}{\partial P_K}FY + \frac{\partial BY_0}{\partial P_K}BY_0 + \sum_i \frac{\partial BY_i}{\partial P_K}BY_i \ \perp \ P_K \geq 0 \tag{12}$$

$$\overline{F} \geq \frac{\partial FY}{\partial P_F}FY \ \perp \ P_F \geq 0 \tag{13}$$

$$\overline{E} \geq \frac{\partial FY}{\partial P_E}FY \ \perp \ P_E \geq 0 \tag{14}$$

$$\overline{S_0} \geq \frac{\partial BY_0}{\partial PS_0}BY_0 \ \perp \ PS_0 \geq 0 \tag{15}$$

$$\overline{S_i} \geq \frac{\partial BY_i}{\partial PS_i}BY_i \ \perp \ PS_i \geq 0, \quad i = 1, 2, 3 \tag{16}$$

$$V \geq \frac{\partial W}{\partial P_V}W \ \perp \ P_V \geq 0 \tag{17}$$

$$FY + BY_0 + \sum_i BY_i \geq \frac{\partial W}{\partial P_Y}W \ \perp \ P_Y \geq 0 \tag{18}$$

$$W \geq \frac{M}{P_W} \ \perp \ P_W \geq 0. \tag{19}$$

We first show that our modeling framework using the hybrid approach can illustrate the "wind

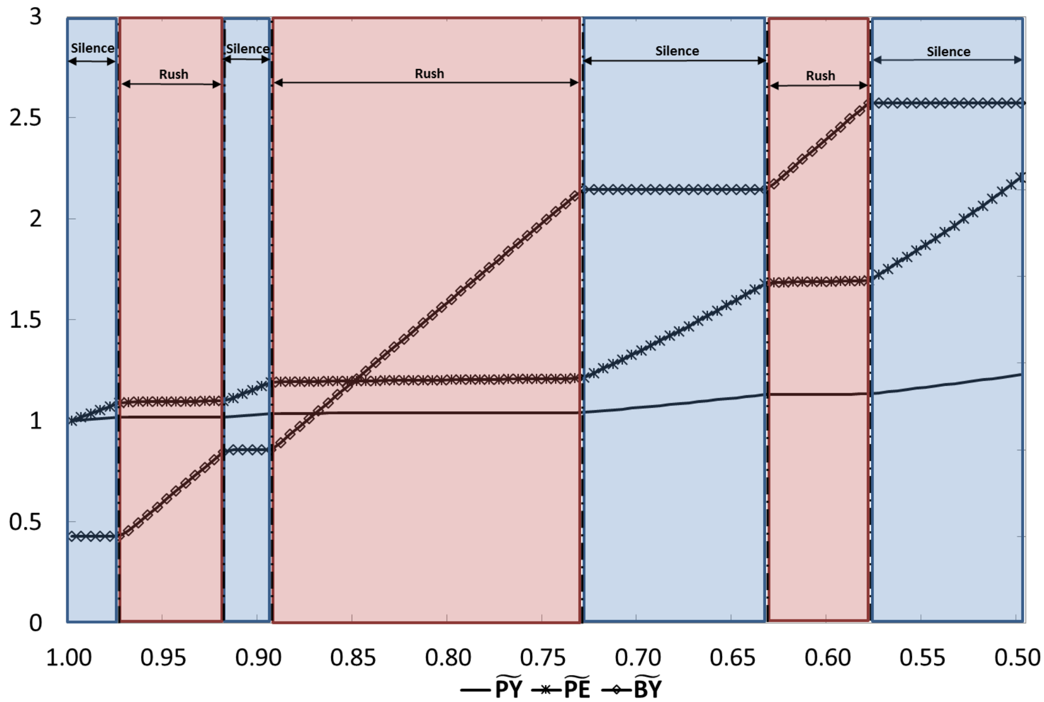

Figure 2. Cyclical increase and stagnation of wind installation ($\tilde{BY}$, right vertical axis), electricity price and emissions allowance price ($\tilde{PY}$ and $\tilde{PE}$, left vertical axis) with narrowing emissions cap (horizontal axis: ratio of emissions cap to the benchmark emissions) .

rush" phenomenon, which usually cannot be represented in the traditional top-down model as the supply curve is smooth. "Wind rush" here refers to the cyclical rapid increase of wind production triggered by subtle changes of policy stringency.

Here we run 100 policy scenarios and gradually lower the emissions cap from 100% to 50% of the benchmark emissions. When simulated, the electricity price increases as a function of the increasing emissions allowance price, and different classes of wind become economic in tandem, as shown in **Figure 2**. The wind production increases rapidly (within a very small range of emissions cap change) until it reaches the potential limit of this level of resource. Meanwhile, the price of emissions allowances as well as the electricity price remains almost constant as the supply of wind increases without incurring more than a trivial cost increase, resulting in a decrease in the supply of fossil-based electricity. When this level of wind resource is exhausted, the price of electricity and emissions allowances start to rise again while the wind installation stagnates, until the next level of wind resource becomes economic. The "rush" and "silence" cycles are displayed in **Figure 2**.

The cost of wind electricity generation remains almost unchanged during the "rush" phase because the prices of labor and capital are relatively stable and the price of another input—a certain grade of wind resource—for the current "rush" phase is zero as this grade of resource is oversupplied as it is exhausted. The evolution of backstop wind resource prices is shown in **Figure 3**.

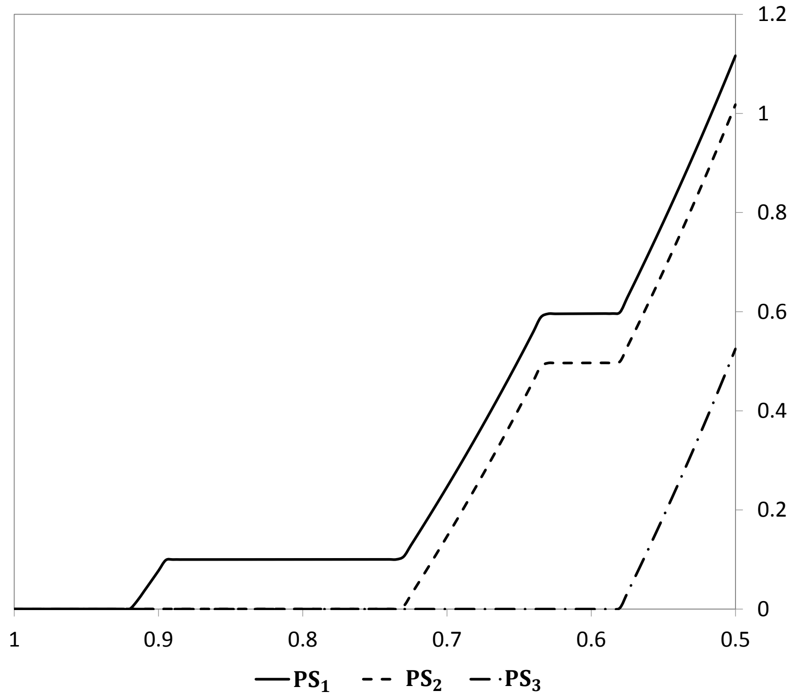

Figure 3. Evolution of backstop wind resource prices of three grades of wind resources (PS1, PS2 and PS3, vertical axis) with narrowing emissions cap (horizontal axis: ratio of emissions cap to the benchmark emissions).

3.2 Comparison with the Traditional Approach

We then compare simulated supply curves derived by the traditional approach using different smooth fitting methods. This traditional approach is widely applied by the CGE modelers as it uses a standard CES function form to fit the original piecewise supply curve.

We first build on the discussion in Boeters and Bollen (2012) to show how a one-level CES production function with a fixed factor in calibrated share form suggested by Rutherford (2008) can be used for fitting. In the cost function below, Y denotes the output (energy); R and V denote natural resource and aggregate of variable inputs, respectively.

$$\tilde{p}_Y = \left(\theta_R \tilde{p}_R^{1-\sigma} + (1-\theta_R)\,\tilde{p}_V^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{20}$$

where θ_R is the value share of the natural resource, and σ is the elasticity of substitution. As the natural resource is fixed at its initial value ($R \equiv 1$), and the variable factors are assumed to have stable prices ($\tilde{p}_V \equiv 1$), we can solve for output[7]:

$$\tilde{Y} = \left[\frac{1-(1-\theta_R)\,\tilde{p}_Y^{\sigma-1}}{\theta_R}\right]^{\frac{\sigma}{1-\sigma}}. \tag{21}$$

[7] This reproduces the calculation of equation #5 in Boeters and Bollen (2012), except that in Boeters and Bollen the denominator θ_R inside the square bracket is not included.

Thus the elasticity of supply is:

$$\eta^s = \sigma \frac{1 - s_R}{s_R} \tag{22}$$

where s_R is the variable value share of the natural source:

$$s_R = 1 - (1 - \theta_R)\, \tilde{p}_Y^{1-\sigma}. \tag{23}$$

One straight-forward fitting method—here we call it the naïve smooth fitting method—assumes $s_R \equiv \theta_R$, so σ can be directly calculated using Equation (22) and η^s estimated by the ordinary least-squares fitting for the supply curve shown in **Figure 1**[8] as follows.

$$\log Y = \alpha + \eta^s \log P_Y + \epsilon \tag{24}$$

where α is the estimated intercept, and ϵ is an error term.

A more precise fitting is to use Equation (21) directly as the functional form when performing least-squares fitting. Here both of θ_R and σ are free variables. We call this fitting method "local smooth" as it still uses the "local" part of original supply curve as the above naïve fitting method.

However, use of the whole original supply curve for fitting is also possible. For the one-level CES production function with a fixed factor in calibrated share form, Boeters and Bollen (2012) shows that there is an upper bound for the output price if $\sigma > 1$:

$$\tilde{p}_Y^{max} = (1 - \theta_R)^{\frac{1}{1-\sigma}}\,. \tag{25}$$

Under this condition, output can be produced with the variable factor alone and has no limit, which is not realistic for the energy production that relies on natural resources. In fact, output usually has an upper limit similar to the original supply curve we design, which implies $\sigma < 1$. The maximum supply can be derived from Equation (21) by setting $\tilde{p}_Y$ to infinity:

$$\tilde{Y}^{max} = \theta_R^{\frac{\sigma}{\sigma-1}}. \tag{26}$$

By applying the maximum supply constraint by Equation (26), we can again use Equation (21) as the functional form for the least-squares fitting. However, here only θ_R or σ is the free variable. We call this fitting method "full-range smooth" as it uses the supply information when the price goes to infinity[9].

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[8] In the vertical direction, the supply curve extends to the infinity. However, we have to truncate the curve and use part of it when the least-squares fitting is applied. Since we have no ex-ante information about how high the electricity price ($\tilde{P}_Y$) will reach relative to the benchmark level, here we choose $\tilde{P}_Y = 1.2$ as the highest bound (covering all the three horizontal steps and a significant part of the last vertical line) for our truncation.

[9] The source code of local smooth and full-range smooth fitting methods can be downloaded from http://www.energyda.com/cge.html.

The θ_R and σ values estimated by the above three smooth fitting methods are shown in **Table 2**.

Table 2. θ_R and σ values estimated by three smooth fitting methods.

	$\boldsymbol{\theta_R}$	σ
Smooth fitting – naïve (SMTN)	0.2	1.25
Smooth fitting – local (SMTL)	0.00174	0.305
Smooth fitting – full-range (SMTF)	0.00001	0.135

Note: θ_R approaches zero in SMTF, therefore, we set a lower bound at a very small level (1E-5) for θ_R and run the estimation.

To represent the wind electricity generation by the CES function using the calibrated θ_R and σ as above, we replace Equation (3) and (4) by the following equation:

$$\Pi^{BY} = P_Y - \left\{ \left(1 - \theta_R^{BY}\right) \left(\tilde{P}_L^{\theta_L^{BY}} \tilde{P}_K^{1-\theta_L^{BY}} \right)^{1-\sigma^{BY}} + \theta_R^{BY} \tilde{P}_{S_0}^{1-\sigma^{BY}} \right\}^{\frac{1}{1-\sigma^{BY}}} \tag{27}$$

where

- θ_R^{BY} is the cost share of resource in production of BY, which is equal to the calibrated value θ_R in **Table 2** for each smooth fitting method,
- θ_L^{BY} is the cost share of labor within the value-added composite in production of BY, and
- σ^{BY} is the elasticity of substitution between the value-added composite and resource in production of BY, which is equal to the calibrated value σ in **Table 2** for each smooth fitting method.

We then run the same 100 policy scenarios to get the simulated supply curve for each smooth fitting method. All the simulated supply curves together with the curve generated using the hybrid approach (represented by STP) are compared in **Figure 4**.

We find that the curve using the naïve fitting method has a different concave shape from all the others, which implies that this widely-used method can lead to potentially significant errors. The local and global fitting methods both generate curves with convex shape, but the curve by the full-range fitting method is systematically deviated to the left to the STP curve, because it is approaching the last vertical part of the piecewise curve at infinity. The local fitting method exhibits much higher accuracy[10].

4. NUMERICAL EXAMPLE OF ONSHORE WIND DEPLOYMENT IN CHINA

In this section, we apply the hybrid approach in a real world example by integrating an estimated multi-step onshore wind supply curve for China into a recursive dynamic multi-sector open-economy CGE model. Supplies of onshore wind in China are estimated in each period under an increasingly stringent emissions control policy. We show how a step-fitting method can be applied to reduce the complexity of the original piecewise supply curve without significantly compromising fidelity. Furthermore, we design additional feed-in-tariff scenarios to incentivize

[10] However, the full-range fitting method may outperform the local fitting one if a very stringent policy can significantly increase the electricity price, which will lead the curve by local fitting method give unrealistic higher supply.

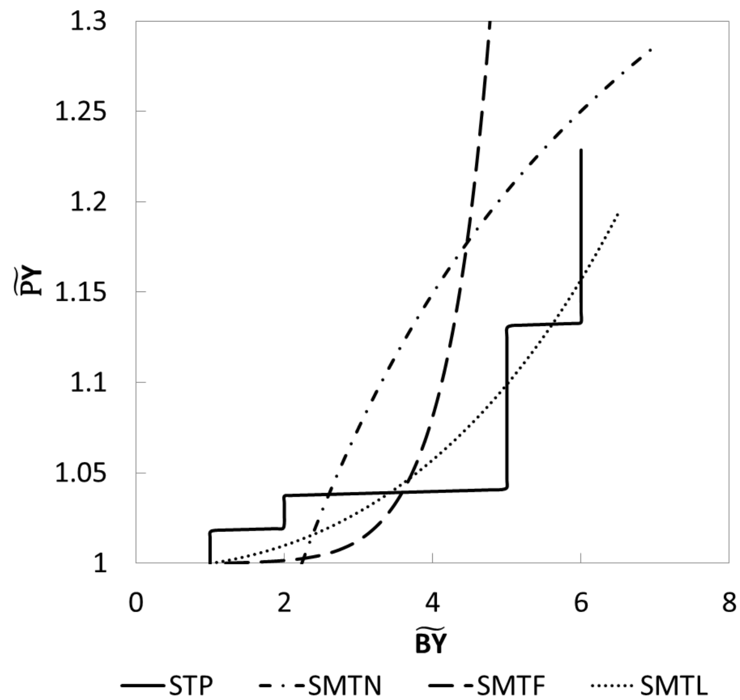

Figure 4. Comparison of the simulated supply curve by the hybrid approach and all the curves by different smooth fitting methods.

more wind deployment and estimate the corresponding total subsidy required. Our results also show that the hybrid approach outweighs the traditional approach when representing renewable resource information with high fidelity, preserving the installed capacity information and capacity to apply flexible FIT policies in top-down models.

4.1 Model

4.1.1 Data

We apply a global energy-economic data set based on the GTAP 8 data base (GTAP, 2012), which provides consistent global accounts of production, consumption and bilateral trade as well as consistent accounts of physical energy flows, energy prices and emissions in the year 2007 (GTAP, 2012). We further aggregate 129 countries in the GTAP data base to two regions (China and rest of the world) and 57 commodities to 10 production sectors (Agriculture, Coal, Crude oil, Natural gas, Electricity, Energy intensive industries, Manufacturing and other secondary industries, Transportation, and Other service industries, see **Table A1)**.

We integrate into the CGE model an onshore wind supply curve for China described in Zhang *et al.* (2014a). This onshore supply curve is derived based on NASA's MERRA (Modern-Era Retrospective analysis for Research and Applications) data set (Rienecker *et al.*, 2011). We truncate this curve to a 306-step piecewise curve which covers the generation cost range from the lowest cost (0.32 yuan/kWh) to 0.80 yuan/kWh, as we believe China's feed-in-tariff will not exceed 0.80 yuan/kWh (2007 price) even under very stringent policy[11]. The supply curve is then shifted upward after accounting for a constant transmission and distribution cost (0.26 yuan/kWh) estimated from the difference between GTAP 8's electricity tariff for China (0.61 yuan/kWh) and China's average generation tariff for coal-based power in 2007 (0.35 yuan/kWh).

4.1.2 Static Model

The static model framework and parameter settings are similar to the CGE model described in Zhang *et al.* (2013) except the treatment of trade, which is simplified as we only include two international regions here. The supply curve for electricity generated from onshore wind is assumed to be a perfect substitute for fossil-based electricity and integrated into the model by the hybrid approach. Detailed formulations of the model can be found in the online appendix[12].

4.1.3 The Dynamic Extension of the Model

We extend the model from 2007 to 2029 by updating the factor supply every two years. For simplicity, we assume a uniform growth rate for all the factors (labor, capital and other sectoral-specific resources) in each time period. Annual growth rates of factors for China and rest of the world in each period are calibrated to match expected GDP growth rates (gradually decreasing from about 10% in 2007 to 4.5% in 2030 for China). A 1%/year improvement in economy-wide energy efficiency, consistent with other models (Sue Wing and Eckaus, 2007), is assumed here. In our policy simulation, we assume that a carbon price is levied from 2009 to 2029 to achieve the emissions reduction path consistent with the Accelerated Effort scenario described in (Zhang *et al.*, 2014b), which is consistent with the targets proposed in U.S.-China Joint Announcement on Climate Change in late 2014. The generation and installed capacity of onshore wind are observed in each time period.

In addition to a carbon tax, we develop two feed-in tariff scenarios to achieve onshore wind deployment targets. The targets are set to be 60 GW for 2011, 80 GW for 2013, 100 GW for 2015 (consistent with the 12th FYP target) and additional 40 GW for every two years after 2015 until 2029 (consistent with the estimated pace of wind deployment; see Zhang *et al.* (2014a)). The subsidy budget for FIT is financed by a tax levied on electricity consumption, and the tax level is endogenously determined in the model to maintain revenue neutrality. A uniform FIT is implemented in the model using the SMTL and STP methods, and a differentiated FIT to achieve the targets with minimal size of subsidy target (the FIT level for each grade of wind is endogenously determined in the model to squeeze the wind resource rent to zero) is implemented in the model using STP as this scenario can only be implemented with the step-curve.

[11] This is verified in our policy simulation. The truncation is actually trivial for the hybrid approach as the tail of the curve never enters production and stays redundant. For the traditional approach, however, the truncation is essential for the accuracy of fitting. The own-price elasticity of supply will differ significantly if the curve is truncated.

[12] The online appendix can be found at http://www.energyda.com/cge.html.

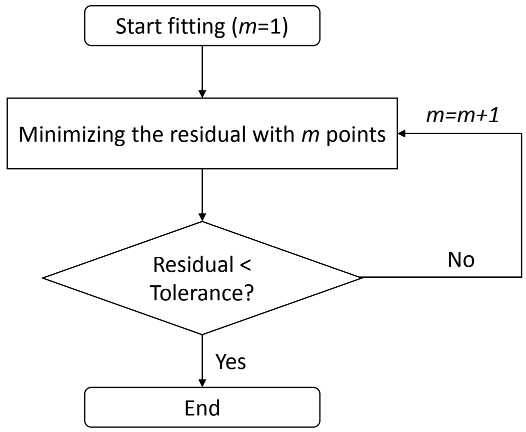

Figure 5. Process chart of the step-fitting method.

4.2 Step-fitting Method

Although the 306-step (let $N = 306$) piecewise onshore wind supply curve in our example is acceptable in terms of computational complexity, here we illustrate how a step-fitting method could further simplify the representation of the curve by using a curve with many fewer steps that is well fitted to the original one within a given tolerance[13].

The process of the step-fitting method can be summarized in **Figure 5**. Since a m-step piecewise curve used to fit the original N-step curve can be determined by m points (the right endpoint of each step), we can find the best-fit m-step curve by optimizing locations of m points to minimize the area between the fitted curve and original curve. The area is defined as $Residual$ here. The optimization problem can be further simplified by finding the vertical coordinates of m points because the horizontal coordinates are endogenously determined. The optimization problem is shown as follows:

$$\min_{\{optLine_m\}} \; Residual = \sum_n (\overline{onshoreCurve}_{n,Gen} - \overline{onshoreCurve}_{n-1,Gen}) * (\overline{onshoreCurve}_{n,P} - optLine_{argmin_m \, |optLine_m - \overline{onshoreCurve}_{n,P}|})$$

$$s.t. \; \overline{onshoreCurve}_{1,P} \leq optLine_m \leq \overline{onshoreCurve}_{N,P}$$

where $optLine_m$ represents the vertical coordinate of the m^{th} point of the fitted curve, $\overline{onshoreCurve}_{n,Gen}$ is the horizontal coordinate of the right endpoint of the original curve's n^{th} step, and $\overline{onshoreCurve}_{n,P}$ is the vertical coordinate of the right endpoint of the original curve's n^{th} step.

We can choose a tolerance of residual representing the required goodness of fit, for example, 1% of the area of the rectangle taken by the original curve. Therefore, $Residual$ should satisfy

[13] The source code of this step-fitting method can be downloaded from http://www.energyda.com/cge.html.

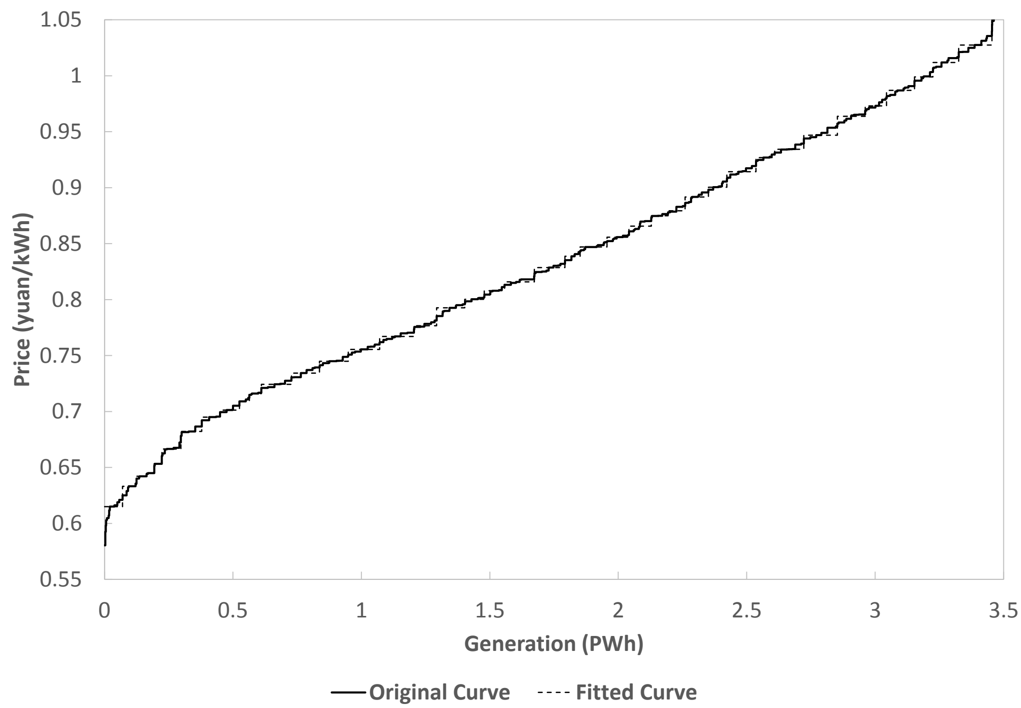

Figure 6. Original and fitted onshore wind supply curve for China.

the following condition:

$$Residual < 0.01 * (\overline{onshoreCurve}_{n,Gen} - \overline{onshoreCurve}_{1,Gen}) * (\overline{onshoreCurve}_{n,P} - \overline{onshoreCurve}_{1,P}).$$

If $Residual$ is not smaller than the tolerance, we start a new optimization problem by introducing one additional free point for the fitted curve. The optimized locations of points in the last iteration are inherited in the new optimization as starting points, and the location of the newly introduced point can be randomly selected. The iteration of optimization stops when $Residual$ is smaller than the tolerance. The fitted function is chosen in order to achieve a 1% level of tolerance, and an 41-step curve is generated using this optimization routine as shown in **Figure 6**.

Similar to the stylized model, we also represent the onshore wind supply curve using the three smooth fitting methods that we described in Section 2. The θ_R and σ values estimated by the above three smooth fitting methods are shown in **Table 3**.

Table 3. θ_R and σ values estimated by three smooth fitting methods.

	θ_R	σ
Smooth fitting – naïve (SMTN)	0.042	0.1769
Smooth fitting – local (SMTL)	0.00378	0.6389
Smooth fitting – full-range (SMTF)	0.0001	0.4352

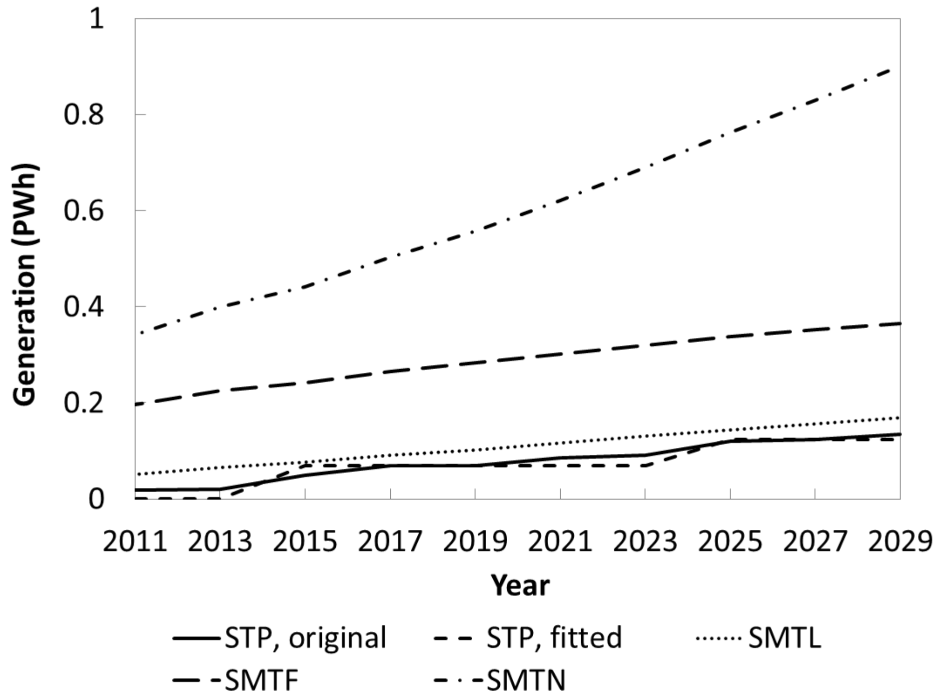

Figure 7. Generation of onshore wind for China in each time period.

4.3 Results

The generation of onshore wind for China in each time period without feed-in tariff under the counterfactural carbon-price only scenario is shown in **Figure 7**. We find that the generation will gradually increase to about 0.12 PWh, roughly 40 GW. The results are robust if we use the fitted curve instead of the original curve with about 30% savings in computation time with an Intel i7-2.80GHz CPU.

Again, the curve estimated using the traditional approach deviates from original and fitted curves generated with the hybrid approach. Of the smooth fitted curves, the local smooth fitting (SMTL) has the least deviation, while the full-range smooth fitting (SMTF) and naïve smooth fitting (SMTN) methods generate significantly devergent results. Moreover, all the smooth fitting methods cannot credibly represent installed capacity as the capacity factor of electricity production cannot be obtained for the equilibrium solution in future years far from the benchmark.

We implement two FIT scenarios to achieve an exogenous path of wind generation targets. The generation target path is translated from a capacity target path starting from about 60 GW in 2011, increasing 20 GW every two years before 2019 and every 40 GW after 2019. The capacity target path is comparable to China's midium-to-long term wind development target. An endogenous subsidy is implemented to support wind generation target achievement, and an endogenous tax on the electricity use is levied to fund the subsidy budget. For a uniform FIT design, a uniform subsidy rate is implemented for all the grades of wind resource and it can be simulated using both the smooth curve (STML) and the step curve (STP). For a differentiated FIT design, which can only be implemented by step curves because they distinguish different grades

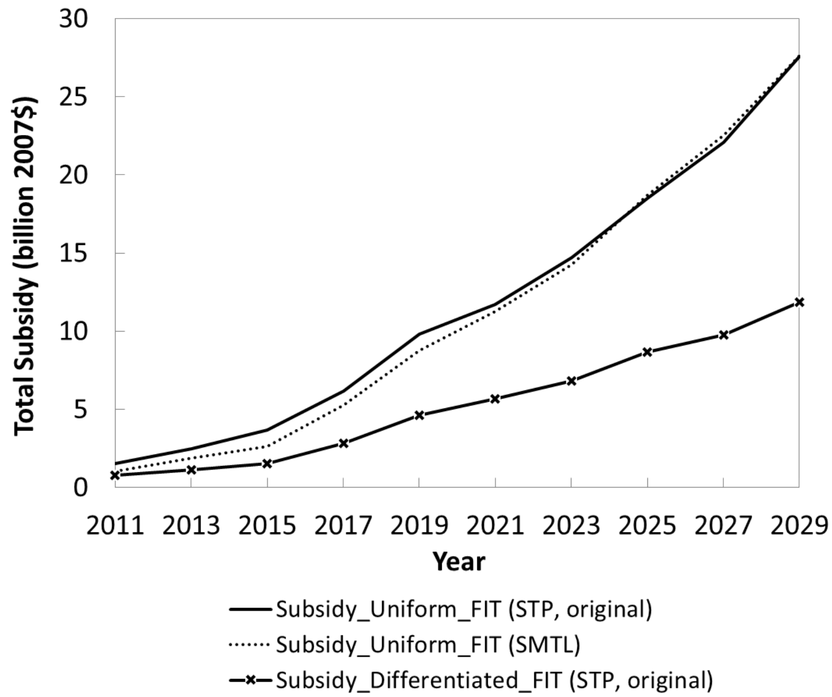

Figure 8. Subsidy budget to achieve China's wind deployment targets.

of resource, differentiated subsidy rates that force the resource rent of all grades of wind resource to zero are endogenously determined in order to find a minimum subsidy budget. The size of the subsidy budget is reported in the two FIT scenarios shown in **Figure 8**. Under a uniform FIT design, about 27.6 billion 2007$ is required estimated by STP and SMTL in 2029. If a differentiated FIT is applied, less than the half of the original subsidy budget, about 11.8 billion 2007$, is required to achieve the same target. We also observe that the welfare loss compared to the BAU scenario is 0.4% (in relative terms) smaller in the differentiated FIT scenario than the uniform FIT scenario, due to the lower policy cost. In both of the FIT scenarios, we also observe that coal consumption increases by 0.4% (about 15 million tce) compared to carbon-price only scenarios. This occurs because the carbon price (which penalizes coal most) falls under the FIT scenarios as more renewables reduce the stringency of the emissions cap. This result is also consistent with the "green promotes the dirtiest" phenomenon described by Böhringer and Rosendahl (2010).

5. CONCLUSION

In this paper, we develop a hybrid method to incorporate technologies that require heterogeneous resources as inputs into top-down economic model that is both efficient and flexible. We show how the hybrid model can represent a "wind rush" phenomenon: as carbon policy stringency increases slightly, the piecewise shape of the supply curve dictates that large quantities of wind capacity will be deployed upon reaching threshold electricity prices almost without raising the CO_2 and energy price. This effect, together with complex cyclical price evolution, is typically not captured by traditional top-down models, which rely on smooth curve fits for resource representation.

We further show that the supply curves derived from policy simulations by the traditional approach (with different smooth fitting methods) can deviate from the real supply curve obtained via the hybrid approach significantly, especially for the fitting method that is widely adopted. If the traditional approach has to be applied, the local smooth fitting method that we introduce in this paper exhibits the best performance (under the condition that the price changes in the simulation do not exceed the range for local smooth fitting very much), especially in the welfare analysis.

Finally, we demonstrate how a piecewise supply curve based on detailed wind resource data can be integrated into a top-down model that includes heterogeneous resource prices and multiple sectors focusing on China's onshore wind electricity as an example. The results suggest that a differentiated FIT design that can only be modeled with the hybrid approach requires less than the half of the subsidy budget and is more cost-effective compared to a uniform FIT design. This has important policy implications as many countries are setting more ambitious targets for renewable and other unconventional forms of energy, which is produced by using natural resources of heterogeneous quality as inputs, and the efficiency of the subsidy budget is of great concern. The hybrid approach also has the advantage that it preserves the inherent physical correspondence between installed capacity and electricity generation information. Moreover, it can be implemented by applying a flexible and computionally inexpensive fitting method.

This hybrid approach has many applications, and can be used to represent resource availability in energy-economy equilirium top-down models in cases where quality-differentiated resource information is available. Extensions could capture important dynamics in the deployment of solar or other low carbon primary energy alternatives, as well as scale up of pollution control technologies and processes. These assessments could alert policymakers to potential bottlenecks that may arise when price signals prompt rapid deployment of targeted technologies or in cases where the features of the supply curve are not amenable to fitting with a smooth functional form.

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Online Appendix

Our algebraic model identifies three categories of conditions for a general equilibrium using a system of inequalities: (i) zero-profit conditions for all the production, (ii) market clearance conditions for all goods and factors and (iii) income balance conditions for all agents. The first class of conditions determine a vector of activity levels, the second determines prices and the third determines incomes. The model equilibrium is formulated as as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995) using the General Algebraic Modeling System (GAMS) and the Mathematical Programming System for General Equilibrium (MPSGE) (Rutherford, 1999). The PATH solver (Dirkse and Ferris, 1995) is used to solve for non-negative prices and quantities.

We state the algebraic exposition of equilibrium conditions below. In the zero-profit conditions, Π^{Z}_{gr} denotes the unit profit function for the production/supply of good g in region r where Z is the associated activity. The partial derivative of the unit profit function with respect to input and output prices provides compensated demand and supply coefficients used in market clearance conditions.

We use g as an index for all sectors plus a private consumption composite, a public good composite and an investment good composite. The index PE represents the subset of primary fossil energy good (coal, crude oil and gas), E represents the subset of final fossil energy good (coal, refined oil, gas and electricity), and FE represents the subset of final fossil energy good except for electricity ELE. $Wind$ represents the electricity from wind production, which is treated as a perfect substitute of fossil-based electricity. For simplicity, we suppress the time index here.

As customary in applied general equilibrium analysis, we use the exogenous elasticities as the free parameters of the functional forms that capture production technologies and consumer preferences. The elasticities in production and consumption CES functions are adopted from the MIT EPPA model (Paltsev *et al.*, 2005) and the value of Armington elasticities are adopted from Caron *et al.* (2015). We recognize that a robust exercise would require the empirical estimation of these elasticities in a structurally similar framework. Such an exercise is out of the scope of the present study.

Table A1 to **Table A10** explain the notations for variables and parameters employed within our algebraic exposition. **Figure A1** to **Figure A4** provide graphical representations of the function forms.

APPENDIX A: Algebraic Exposition of Equilibrium Conditions

Zero profit conditions

1. Production of agriculture goods ($Y_{gr}\,|_{g=AGR}$):

$$
\begin{aligned}
\Pi^Y_{gr} &= \frac{P^Y_{gr}(1-t^Y_{gr})}{\overline{P^Y_{gr}}} \\
&- \Bigg(\theta^{va}_{gr}\Bigg(\Big(\theta^L_{gr}\Big(\frac{P^L_r(1+t^L_{gr})}{\overline{P^L_{gr}}}\Big)^{1-\sigma^{va}} + (1-\theta^L_{gr})\Big(\frac{P^K_r(1+t^K_{gr})}{\overline{P^K_{gr}}}\Big)^{1-\sigma^{va}}\Big)^{\frac{1}{1-\sigma^{va}}}\Bigg)^{1-\sigma^{erva}} \\
&+ (1-\theta^{va}_{gr})\Bigg(\Big(\theta^R_{gr}\Big(\frac{P^R_{gr}(1+t^R_{gr})}{\overline{P^R_{gr}}}\Big)^{1-\sigma^{er}} + (1-\theta^R_{gr})\big((\theta^E_{gr}P^E_{gr}{}^{1-\sigma^{ae}} \\
&+ (1-\theta^E_{gr})\Big(\sum_{i\notin E}\theta^A_{igr}P^A_{igr}\Big)^{1-\sigma^{ae}}\big)^{\frac{1}{1-\sigma^{ae}}}\big)^{1-\sigma^{er}}\Big)^{\frac{1}{1-\sigma^{er}}}\Bigg)^{1-\sigma^{erva}}\Bigg)^{\frac{1}{1-\sigma^{erva}}} \\
&\le 0 \quad \perp \quad Y_{gr} \ge 0
\end{aligned}
$$

2. Production of fossil fuels ($Y_{gr}\,|_{g\in PE}$)

$$
\begin{aligned}
\Pi^Y_{gr} &= \frac{P^Y_{gr}(1-t^Y_{gr})}{\overline{P^Y_{gr}}} - \Bigg(\theta^R_{gr}\Big(\frac{P^R_{gr}(1+t^R_{gr})}{\overline{P^R_{gr}}}\Big)^{1-\sigma^{fr}} \\
&+ (1-\theta^R_{gr})\Bigg(\sum_i \theta^A_{igr}P^A_{igr} + \theta^{va}_{gr}\Big(\theta^L_{gr}\Big(\frac{P^L_r(1+t^L_{gr})}{\overline{P^L_{gr}}}\Big)^{1-\sigma^{va}} \\
&+ (1-\theta^L_{gr})\Big(\frac{P^K_r(1+t^K_{gr})}{\overline{P^K_{gr}}}\Big)^{1-\sigma^{va}}\Big)^{\frac{1}{1-\sigma^{va}}}\Bigg)^{1-\sigma^{fr}}\Bigg)^{\frac{1}{1-\sigma^{fr}}} \\
&\le 0 \quad \perp \quad Y_{gr} \ge 0
\end{aligned}
$$

3. Production of other goods ($Y_{gr}\,|_{g\notin\{AGR,PE\}}$):

$$
\begin{aligned}
\Pi^Y_{gr} &= \frac{P^Y_{gr}(1-t^Y_{gr})}{\overline{P^Y_{gr}}} - \Bigg(\sum_{i\notin E}\theta^A_{igr}P^A_{igr} \\
&+ \theta^{eva}_{gr}\Bigg(\theta^{va}_{gr}\Big(\big(\theta^L_{gr}\Big(\frac{P^L_r(1+t^L_{gr})}{\overline{P^L_{gr}}}\Big)^{1-\sigma^{va}} \\
&+ (1-\theta^L_{gr})\Big(\frac{P^K_r(1+t^K_{gr})}{\overline{P^K_{gr}}}\Big)^{1-\sigma^{va}}\big)^{\frac{1}{1-\sigma^{va}}}\Big)^{1-\sigma^{eva}} + (1-\theta^{va}_{gr})P^E_{gr}{}^{1-\sigma^{eva}}\Bigg)^{\frac{1}{1-\sigma^{eva}}}\Bigg) \\
&\le 0 \quad \perp \quad Y_{gr} \ge 0
\end{aligned}
$$

4. Production of wind represented by a smooth curve ($Y_{Wind^{SM}r}$):

$$\begin{aligned}
\Pi^{Y}_{Wind^{SM}r} &= P^{Y}_{ELEr}(1-\psi^{Wind^{SM}}_{r}) \\
&- \overline{\mu^{Wind^{SM}r}}\Big(\theta^{va}_{Wind^{SM}r}\Big(\big(\theta^{L}_{Wind^{SM}r}P^{L}_{r}{}^{1-\sigma^{va}} \\
&+ (1-\theta^{L}_{Wind^{SM}r})P^{K}_{r}{}^{1-\sigma^{va}}\big)^{\frac{1}{1-\sigma^{va}}}\Big)^{1-\sigma^{Wind^{SM}r}} + (1-\theta^{va}_{Wind^{SM}r})P^{R}_{Wind^{SM}r}{}^{1-\sigma^{Wind^{SM}r}}\Big)^{\frac{1}{1-\sigma^{Wind^{SM}r}}} \\
&\leq 0 \quad \perp \quad Y_{Wind^{SM}r} \geq 0
\end{aligned}$$

5. Production of wind represented by a step curve (the nth step) ($Y_{Wind^{ST}nr}$):

$$\begin{aligned}
\Pi^{Y}_{Wind^{ST}nr} &= P^{Y}_{ELEr}(1-\psi^{Wind^{ST}}_{r})(1-\psi^{Wind^{ST}}_{nr}) \\
&- \overline{\mu^{Wind^{ST}nr}}\Big(\theta^{va}_{Wind^{ST}nr}\big(\theta^{L}_{Wind^{ST}nr}P^{L}_{r}{}^{1-\sigma^{va}} \\
&+ (1-\theta^{L}_{Wind^{ST}nr})P^{K}_{r}{}^{1-\sigma^{va}}\big)^{\frac{1}{1-\sigma^{va}}} + (1-\theta^{va}_{Wind^{ST}nr})P^{R}_{Wind^{ST}nr}\Big) \\
&\leq 0 \quad \perp \quad Y_{Wind^{ST}nr} \geq 0
\end{aligned}$$

6. Sector-specific energy aggregate (E_{gr}):

$$\begin{aligned}
\Pi^{E}_{gr} = P^{E}_{gr} &- \Bigg(\Big(\theta^{ELE}_{gr}P^{A}_{ELEr}(1+\tau^{ELE^{SM}}_{r})(1+\tau^{ELE^{ST}}_{r})(1+\tau^{ELE^{ST'}}_{r})\Big)^{1-\sigma^{enoe}} \\
&+ (1-\theta^{ELE}_{gr})\Big(\Big(\theta^{COA}_{gr}\big(P^{A}_{COAr}+\alpha^{CO_2}_{COAr}P^{CO_2}_{r}\big)^{1-\sigma^{en}} + \theta^{OIL}_{gr}\big(P^{A}_{OILr}+\alpha^{CO_2}_{OILr}P^{CO_2}_{r}\big)^{1-\sigma^{en}} \\
&+ \theta^{GAS}_{gr}\big(P^{A}_{GASr}+\alpha^{CO_2}_{GASr}P^{CO_2}_{r}\big)^{1-\sigma^{en}}\Big)^{\frac{1}{1-\sigma^{en}}}\Big)^{1-\sigma^{enoe}}\Bigg)^{\frac{1}{1-\sigma^{enoe}}} \\
&\leq 0 \quad \perp \quad E_{gr} \geq 0
\end{aligned}$$

7. Armington aggregate (A_{igr}):

$$\begin{aligned}
\Pi^{A}_{igr} = P^{A}_{igr} &- \left(\theta^{DM}_{igr}\left(\frac{P^{Y}_{ir}(1+t^{DM}_{igr})}{\overline{P^{Y}_{igr}}}\right)^{1-\sigma^{DM}} + (1-\theta^{DM}_{igr})\left(\frac{P^{MM}_{ir}(1+t^{MM}_{igr})}{\overline{P^{MM}_{igr}}}\right)^{1-\sigma^{DM}}\right)^{\frac{1}{1-\sigma^{DM}}} \\
&\leq 0 \quad \perp \quad A_{igr} \geq 0
\end{aligned}$$

8. Import aggregate (MM_{ir}):

$$\Pi_{ir}^{MM} = P_{ir}^{MM} - \left(\sum_s \theta_{isr}^{MM} \left(\theta_{isr}^{T} P^{YT} + (1-\theta_{isr}^{YT}) \frac{P_{is}^{Y}(1-t_{isr}^{XS})(1+t_{isr}^{MS})}{\overline{P_{isr}^{Y}}} \right)^{1-\sigma^{MM}} \right)^{\frac{1}{1-\sigma^{MM}}}$$
$$\leq 0 \;\; \perp \;\; MM_{ir} \geq 0$$

9. International transportation service (YT):

$$\Pi^{YT} = P^{YT} - \prod_r \left(P_{TRNr}^{Y} \right)^{\alpha_{TRNr}^{YT}} \leq 0 \;\; \perp \;\; YT \geq 0$$

10. Labor supply (L_r):

$$\Pi_r^{L} = P_r^{L} - P_r^{LS} \leq 0 \;\; \perp \;\; L_r \geq 0$$

11. Welfare (W_r):

$$\Pi_r^{W} = P_r^{W} - \left(P_{Ir}^{Y} \right)^{\alpha_{Ir}^{W}} \left(\left(\theta_r^{LS} P_r^{LS\,1-\sigma^{LS}} + (1-\theta_r^{LS}) P_{Cr}^{Y\;1-\sigma^{LS}} \right)^{\frac{1}{1-\sigma^{LS}}} \right)^{1-\alpha_{Ir}^{W}}$$
$$\leq 0 \;\; \perp \;\; W_r \geq 0$$

Market clearance conditions

12. Labor (P_r^L):

$$L_r \geq \sum_g Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial (P_r^{L}(1+t_{gr}^{L}))} \;\; \perp \;\; P_r^{L} \geq 0$$

13. Leisure (P_r^{LS}):

$$\overline{L_r} - L_r \geq W_r \frac{\partial \Pi_r^{W}}{\partial P_r^{LS}} \;\; \perp \;\; P_r^{LS} \geq 0$$

14. Capital (P_r^K):

$$\overline{K_r} \geq \sum_g Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial (P_r^{K}(1+t_{gr}^{K}))} \;\; \perp \;\; P_r^{K} \geq 0$$

15. Sectoral-specific resource (P_{gr}^R):

$$\overline{R_{gr}} \geq \sum_g Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial (P_{gr}^{R}(1+t_{gr}^{R}))} \;\; \perp \;\; P_{gr}^{R} \geq 0$$

16. Energy composite (P_{gr}^{E}):

$$E_{gr} \geq \sum_{g} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial P_{gr}^{E}} \quad \perp \quad P_{gr}^{E} \geq 0$$

17. Armington good (P_{ir}^{A}):

$$A_{igr} \geq \sum_{g} E_{gr} \frac{\partial \Pi_{gr}^{E}}{\partial (P_{igr}^{A} + \alpha_{ir}^{CO_2} P_{r}^{CO_2})} + \sum_{g} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial P_{igr}^{A}} \quad \perp \quad P_{ir}^{A} \geq 0$$

18. Import aggregate (P_{ir}^{MM}):

$$MM_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial (P_{ir}^{MM}(1 + t_{igr}^{MM}))} \quad \perp \quad P_{ir}^{MM} \geq 0$$

19. Commodities (P_{ir}^{Y}):

$$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial (P_{ir}^{Y}(1 - t_{ir}^{Y}))} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial (P_{ir}^{Y}(1 + t_{igr}^{DM}))} + \sum_{s} MM_{is} \frac{\partial \Pi_{is}^{MM}}{\partial (P_{ir}^{Y}(1 - t_{irs}^{XS})(1 + t_{irs}^{MS}))} \quad \perp \quad P_{ir}^{Y} \geq 0$$

20. Private consumption (P_{Cr}^{Y}):

$$Y_{Cr} \geq W_{r} \frac{\partial \Pi_{r}^{W}}{\partial P_{Cr}^{Y}} \quad \perp \quad P_{Cr}^{Y} \geq 0$$

21. Investment (P_{Ir}^{Y}):

$$Y_{Ir} \geq W_{r} \frac{\partial \Pi_{r}^{W}}{\partial P_{Ir}^{Y}} \quad \perp \quad P_{Ir}^{Y} \geq 0$$

22. Government consumption (P_{Gr}^{Y}):

$$Y_{Gr} \geq \frac{INC_{r}^{G}}{P_{Gr}^{Y}} \quad \perp \quad P_{Gr}^{Y} \geq 0$$

23. Welfare (P_{r}^{W}):

$$W_{r} \geq \frac{INC_{r}^{RA}}{P_{r}^{W}} \quad \perp \quad P_{r}^{W} \geq 0$$

24. Carbon emissions ($P_{r}^{CO_2}$):

$$\overline{CO_2} \geq \sum_{r} \sum_{i \in FE} \sum_{g} E_{gr} \frac{\partial \Pi_{gr}^{E}}{\partial (P_{igr}^{A} + \alpha_{ir}^{CO_2} P_{r}^{CO_2})} \quad \perp \quad P_{r}^{CO_2} \geq 0$$

Income-expenditure balances

25. Income of representative consumer (INC_r^{RA}):

$$INC_r^{RA} = P_r^{LS}\overline{L_r} + P_r^K\overline{K_r} + \sum_g P_{gr}^R\overline{R_{gr}} + P_r^{CO_2}\overline{CO_2} + \overline{BOP_r^{RA}} + \chi_r\overline{TRNF_r}$$

26. Income of government (INC_r^G):

$$\begin{aligned} INC_r^G = {} & \sum_g Y_{gr}\frac{\partial\Pi_{gr}^Y}{\partial(P_r^L(1+t_{gr}^L))}P_r^L t_{gr}^L + \sum_g Y_{gr}\frac{\partial\Pi_{gr}^Y}{\partial(P_r^L(1+t_{gr}^L))}P_r^K t_r^K \\ & + \sum_g \overline{R_{gr}}P_{gr}^R t_{gr}^R + \sum_g Y_{gr}\frac{\partial\Pi_{gr}^Y}{\partial(P_{gr}^Y(1-t_{gr}^Y))}P_{gr}^Y t_{gr}^Y \\ & + \sum_i\sum_g\left(A_{igr}\frac{\partial\Pi_{igr}^A}{\partial(P_{ir}^Y(1+t_{igr}^{DM}))}P_{ir}^Y t_{igr}^{DM} + A_{igr}\frac{\partial\Pi_{igr}^A}{\partial(P_{ir}^{MM}(1+t_{igr}^{MM}))}P_{ir}^Y t_{igr}^{MM}\right) \\ & + \sum_s\sum_i MM_{ir}\frac{\partial\Pi_{ir}^{MM}}{\partial(P_{is}^Y(1-t_{isr}^{XS})(1+t_{isr}^{MS}))}P_{is}^Y(1-t_{isr}^{XS})t_{isr}^{MS}) \\ & - \sum_s\sum_i MM_{is}\frac{\partial\Pi_{is}^{MM}}{\partial(P_{ir}^Y(1-t_{irs}^{XS})(1+t_{irs}^{MS}))}P_{ir}^Y t_{irs}^{XS}) \\ & - \chi_r\overline{TRNF_r} \end{aligned}$$

Other constraints

27. Equal-yield for government demand (χ_r):

$$\frac{INC_r^G}{P_{Gr}^Y} = \overline{G_r} \quad \perp \quad \chi_r$$

28. Wind generation target is achieved by subsidy ($\psi_r^{Wind^{SM}}$,$\psi_r^{Wind^{ST}}$,$\psi_{nr}^{Wind^{ST}}$):

$$Y_{Wind^{SM}r}\frac{\partial\Pi_{Wind^{SM}r}^Y}{\partial(P_{ELEr}^Y(1-\psi_r^{Wind^{SM}}))} = \overline{Y_{Windr}} \quad \perp \quad \psi_r^{Wind^{SM}}$$

$$\sum_n Y_{Wind^{ST}nr}\frac{\partial\Pi_{Wind^{ST}nr}^Y}{\partial(P_{ELEr}^Y(1-\psi_r^{Wind^{ST}}))} = \overline{Y_{Windr}} \quad \perp \quad \psi_r^{Wind^{ST}}$$

$$\frac{Y_{Wind^{ST}N_{mr}r}}{\overline{\overline{Y_{Wind^{ST}N_{mr}r}}}} = 1 \quad \perp \quad \psi_{N_{mr}r}^{Wind^{ST}} \quad \left(N_{mr} = argmin_n\left(\sum_n Y_{Wind^{ST}nr}\frac{\partial\Pi_{Wind^{ST}nr}^Y}{\partial(P_{ELEr}^Y(1-\psi_{nr}^{Wind^{ST}}))} \geq \overline{Y_{Windr}}\right)\right)$$

$$P^R_{Wind^{ST}nr} = 1e-5 \;\perp\; \psi^{Wind^{ST}}_{nr} \; (n = 1, 2, 3, ..., N_{m-1r})$$

29. Wind subsidy budget balance ($\tau^{ELE^{SM}}_r$,$\tau^{ELE^{ST}}_r$,$\tau^{ELE^{ST'}}_r$):

$$Y_{Wind^{SM}r}\frac{\partial \Pi^Y_{Wind^{SM}r}}{\partial(P^Y_{ELEr}(1-\psi^{Wind^{SM}}_r))}P^Y_{ELEr}\psi^{Wind^{SM}}_r = \sum_g A_{ELEgr}P^A_{ELEr}\tau^{ELE^{SM}}_r \;\perp\; \tau^{ELE^{SM}}_r$$

$$\sum_n Y_{Wind^{ST}nr}\frac{\partial \Pi^Y_{Wind^{ST}nr}}{\partial(P^Y_{ELEr}(1-\psi^{Wind^{ST}}_r))}P^Y_{ELEr}\psi^{Wind^{ST}}_r = \sum_g A_{ELEgr}P^A_{ELEr}\tau^{ELE^{ST}}_r \;\perp\; \tau^{ELE^{ST}}_r$$

$$\sum_n Y_{Wind^{ST}nr}\frac{\partial \Pi^Y_{Wind^{ST}nr}}{\partial(P^Y_{ELEr}(1-\psi^{Wind^{ST}}_{nr}))}P^Y_{ELEr}\psi^{Wind^{ST}}_{nr} = \sum_g A_{ELEgr}P^A_{ELEr}\tau^{ELE^{ST'}}_r \;\perp\; \tau^{ELE^{ST'}}_r$$

APPENDIX B: Notations

Table A1. Sectors in the numerical model.

Abbreviation	Sector
AGR	Agriculture
COL	Coal
CRU	Crude oil
GAS	Natural gas
OIL	Petroleum and coal products
ELE	Electricity
EIS	Energy intensive industries, e.g. iron and steel, non-ferrous metal, metal products and non-metallic materials
MAN	Manufacturing and other secondary industries
TRN	Transportation
SER	Other service industries

Table A2. Sets in the numerical model.

Symbol	Description
i	Goods (all sectors plus wind electricity production) excluding final demand goods
g	Goods including intermediate goods ($g = i$) and final demand goods, i.e. private consumption ($g = C$), investment ($g = I$) and public consumption ($g = G$)
r (alias s)	Region
PE	Primary energy goods (coal, crude oil and gas)
E	Final energy goods (coal, refined oil, gas and electricity)
FE	Final energy goods except electricity (coal, refined oil and gas)

Table A3. Activity variables in the numerical model.

Symbol	Description
Y_{gr}	Production of good g in region r
E_{gr}	Production of energy composite for good g in region r
A_{igr}	Production of Armington good i for good g region r
MM_{ir}	Production of import composite good i in region r
YT	Production of international transportation service
L_r	Labor supply in region r
W_r	Production of composite welfare (utility) good in region r

Table A4. Price variables in the numerical model.

Symbol	Description
p_{gr}^{Y}	Price of good g in region r
p_{gr}^{E}	Price of energy composite for good g in region r
p_{igr}^{A}	Price of Armington good i for good g in region r
p_{ir}^{MM}	Price of import composite good i in region r
p^{YT}	Price of international transportation service
p_{r}^{L}	Price of labor (wage rate) in region r
p_{r}^{LS}	Price of leisure in region r
p_{r}^{K}	Price of capital service (rental rate) in region r
p_{gr}^{R}	Rent to sectoral-specific resources in sector g and region r
$p_{r}^{CO_2}$	CO_2 price in region r
p_{r}^{W}	Price of composite welfare (utility) good in region r

Table A5. Income variables in the numerical model.

Symbol	Description
INC_{r}^{RA}	Income of representative agent in region r
INC_{r}^{G}	Income of government in region r

Table A6. Tax rates and reference prices in the numerical model.

Symbol	Description
t_{gr}^{Y}	Taxes on output for good g in region r
t_{gr}^{L}	Taxes on labor input for good g in region r
t_{gr}^{K}	Taxes on capital input for good g in region r
t_{gr}^{R}	Taxes on resource input for good g in region r
t_{igr}^{DM}	Taxes on intermediate use of domestic good i for good g in region r
t_{igr}^{MM}	Taxes on intermediate use of import composite good i for good g in region r
t_{isr}^{XS}	Taxes on export good i from region s to region r
t_{isr}^{MS}	Taxes on import good i from region s to region r
$\overline{p_{gr}^{Y}}$	Reference price of good g in region r
$\overline{p_{gr}^{L}}$	Reference price of labor (wage rate) for good g in region r
$\overline{p_{gr}^{K}}$	Reference price of capital (rental rate) for good g in region r
$\overline{p_{gr}^{R}}$	Reference price of resource rent for good g in region r
$\overline{p_{igr}^{A}}$	Reference price of Armington good i for good g in region r
$\overline{p_{igr}^{Y}}$	Reference price of domestic good i for good g in region r
$\overline{p_{igr}^{MM}}$	Reference price of import composite good i for good g in region r
$\overline{p_{isr}^{Y}}$	Reference price of import good i from region s to region r

Table A7. Cost shares in the numerical model.

Symbol	Description
θ_{gr}^{L}	Value share of labor in the value-added composite for good g in region r
θ_{gr}^{va}	Value share of value-added composite for good g in region r
θ_{gr}^{R}	Value share of resource rent for good g in region r
θ_{gr}^{E}	Value share of energy input for good g in region r
θ_{igr}^{A}	Value share of intermediate input Armington good i for good g in region r
θ_{gr}^{ELE}	Value share of electricity in the energy aggregate for good g in region r
θ_{gr}^{COA}	Value share of coal in the energy aggregate for good g in region r
θ_{gr}^{OIL}	Value share of refined oil in the energy aggregate for good g in region r
θ_{gr}^{GAS}	Value share of gas in the energy aggregate for good g in region r
θ_{igr}^{DM}	Value share of domestic good in Armington composite good i for good g in region r
θ_{igr}^{MM}	Value share of import composite in Armington composite good i for good g in region r
θ_{isr}^{MM}	Value share of import good in import composite good i from region s to region r
θ_{isr}^{YT}	Value share of international transportation service in import good i from region s to region r
α_{TRNr}^{YT}	Value share of transport service from region r in international transportation service
θ_{r}^{LS}	Value share of leisure in consumption-leisure composite in region r
α_{Ir}^{W}	Value share of investment in utility composite in region r

Table A8. Endowments and emissions coefficients in the numerical model.

Symbol	Description
$\overline{L_r}$	Aggregate time (labor and leisure) endowment of region r
$\overline{K_r}$	Aggregate capital endowment of region r
$\overline{R_{gr}}$	Aggregate resource endowment for good g of region r
$\overline{\mu^{Wind^{SM}r}}$	Mark-up cost coefficient for wind generation represented by a smooth curve in region r
$\overline{\mu^{Wind^{ST}nr}}$	Mark-up cost coefficient for wind generation represented by a step curve (the nth step) in region r
$\overline{BOP_r^{RA}}$	Representative agent's balance of payment deficit or surplus in region r
$\overline{TRNF_r}$	Transfer from government to representative agent in region r
$\overline{G_r}$	Public good consumption from the baseline in region r
$\overline{CO_{2r}}$	Endowment with carbon emissions permits in region r
$\overline{\alpha_{ir}^{CO_2}}$	Carbon emissions coefficient for fossil fuel i in region r
$\overline{Y_{Windr}}$	Wind generation target in region r

Table A9. Substitution elasticities in the numerical model.

Parameter	Substitution margin	Value
σ^{en}	Energy (excluding electricity)	1.0
σ^{enoe}	Energy—electricity	0.5
σ^{eva}	Energy/electricity—value-added	0.5
σ^{va}	Capital—labor	1.0
σ^{klem}	Capital/labor/energy—materials	0
σ^{ae}	Energy/electricity—materials in AGR	0.3
σ^{er}	Energy/materials—land resource in AGR	0.6
σ^{fr}	Capital/labor/materials—resource in primary energy	Calibrated
$\sigma^{Wind^{SM}r}$	Capital/labor—resource in wind generation represented by a smooth curve	Calibrated
σ^{govinv}	Materials—energy in government and investment demand	0.5
σ^{ct}	Transportation—Non-transport in private consumption	1.0
σ^{ec}	Energy—Non-energy in private consumption	0.25
σ^{c}	Non-energy in private consumption	0.25
σ^{ef}	Energy in private consumption	0.4
σ^{DM}	Foreign—domestic	GTAP, version 8
σ^{MM}	Across foreign origins	GTAP, version 8
σ^{LS}	Leisure—material consumption	0.8

Note: Substitution elasticity for fossil fuel resource factors are calibrated using estimates for price elasticities of supply: 1 for coal and natural gas and 0.5 for crude oil suggested by the MIT EPPA model (Paltsev *et al.*, 2005).

Table A10. Additional variables in the numerical model.

Symbol	Description
χ_r	Lump-sum transfer to warrant equal-yield constraint for government in region r
$\psi_r^{Wind^{SM}}$	Uniform subsidy for wind generation represented by a smooth curve to warrant an exogenous generation target in region r
$\psi_r^{Wind^{ST}}$	Uniform subsidy for wind generation represented by a step curve to warrant an exogenous generation target in region r
$\psi_{nr}^{Wind^{ST}}$	Differentiated tax/subsidy for wind generation represented by a step curve to warrant an exogenous generation target and zero resource rent in region r
$\tau_r^{ELE^{SM}}$	Tax on the electricity use to finance a uniform subsidy for wind generation represented by a smooth curve in region r
$\tau_r^{ELE^{ST}}$	Tax on the electricity use to finance a uniform subsidy for wind generation represented by a step curve in region r
$\tau_r^{ELE^{ST'}}$	Tax on the electricity use to finance a differentiated tax/subsidy for wind generation represented by a step curve in region r

APPENDIX C: Graphical Representations of the Function Forms

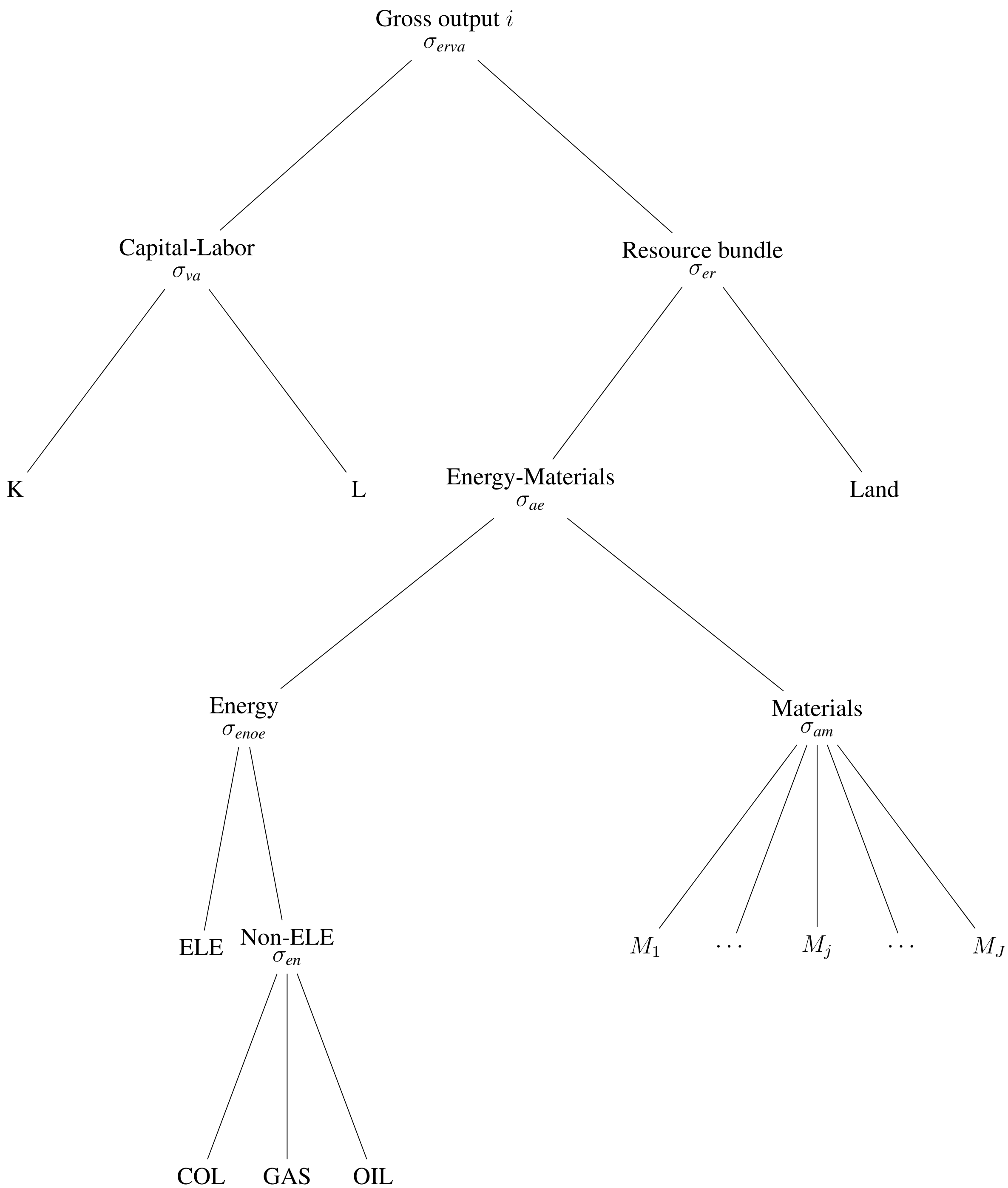

Figure A1. Structure of production for $i \in \{\text{AGR}\}$.

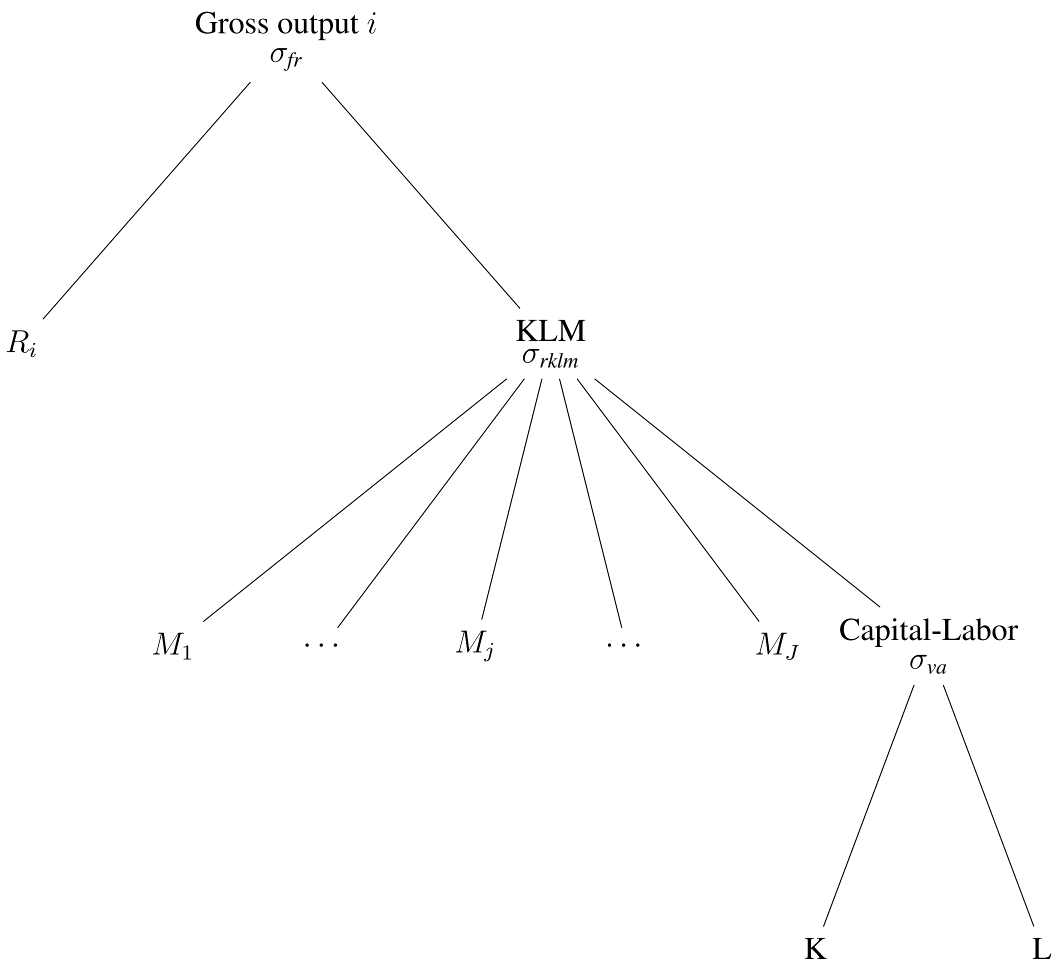

Figure A2. Structure of primary energy sectors $i \in PE$.

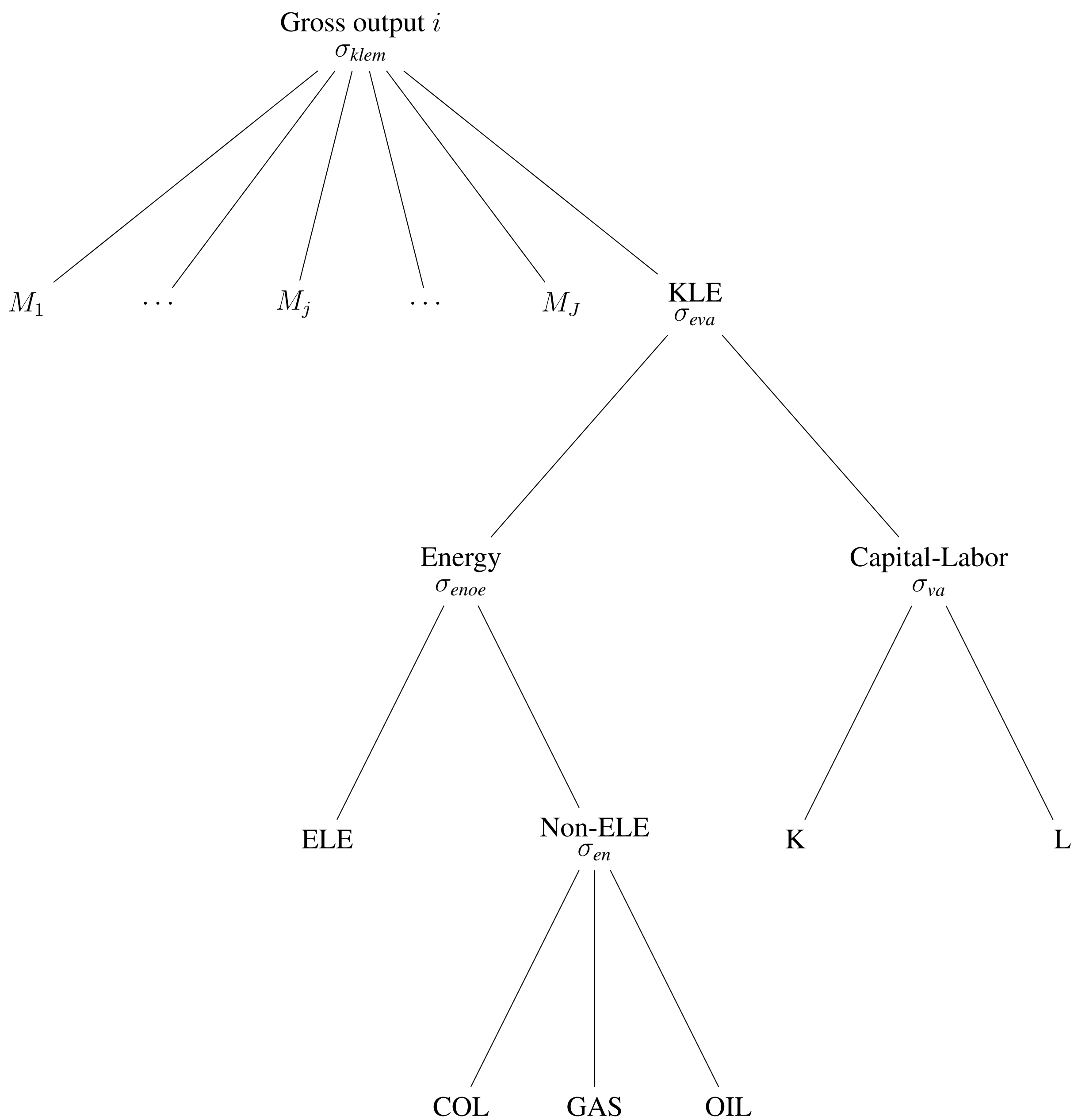

Figure A3. Structure of production for $i \notin \{AGR, PE\}$.

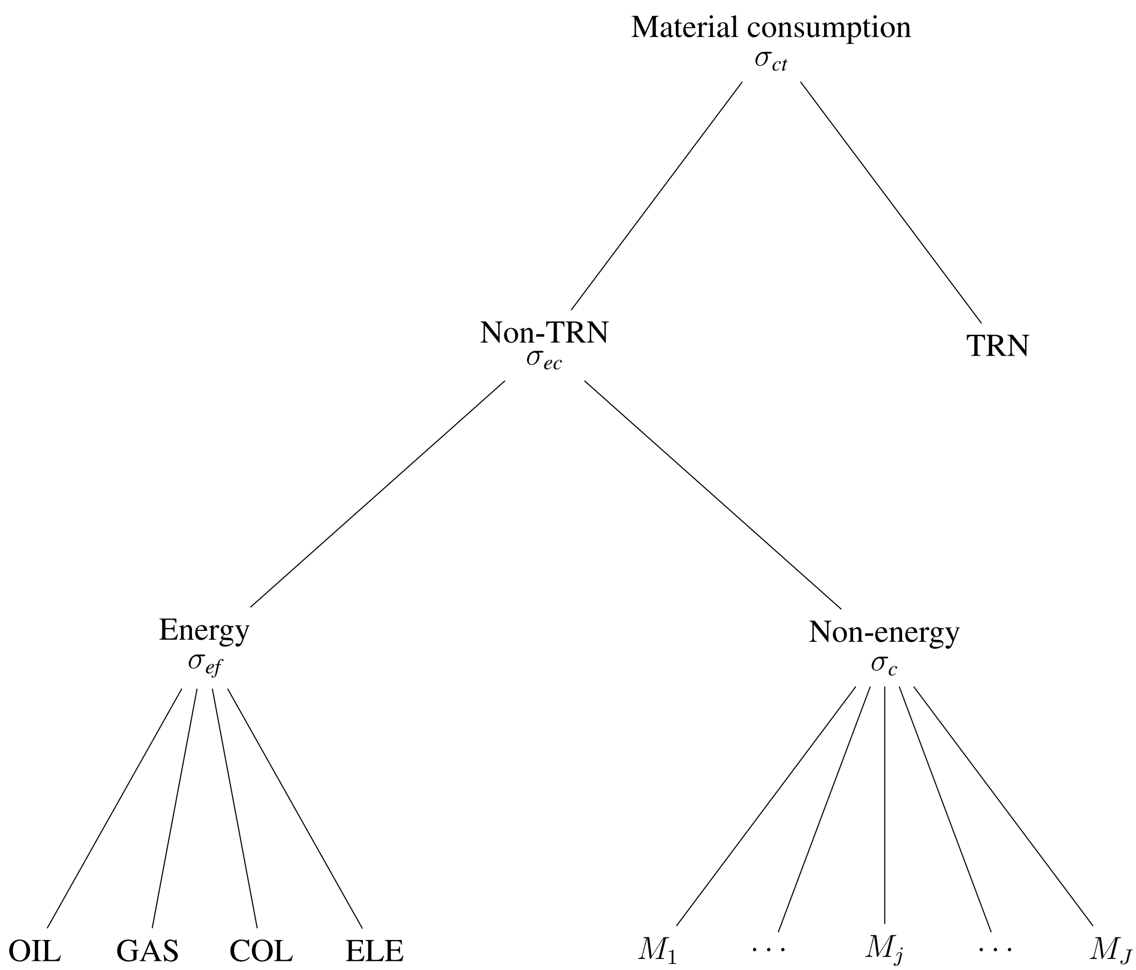

Figure A4. Structure of private material consumption.

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